Three Decades of Measuring In Situ Stresses and Monitoring Stress Changes with the ANZI Strain Cell

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Abstract: This paper describes the development of the ANZI (Australia, New Zealand Inflatable) strain cell over the past three decades and the operation of the instrument including some examples of its application. The ANZI strain cell is used for measuring strain changes in rock on borehole walls suitable for estimating in situ stresses and stress changes. The instrument comprises a pressuremeter design that allows electrical resistance strain gauges to be pressure bonded directly to the rock on a borehole wall. The strain gauges are monitored during overcoring to obtain stress relief strains for estimation of the in situ stress. In monitoring applications, strain changes within a rock mass induced by mining and other construction activities are measured over time.

The instrument's soft polyurethane membrane and hollow pressuremeter design have a number of characteristics that facilitate deployment, enhance data gathering, and simplify analysis. The membrane is soft enough to be ignored in any analysis and yet stiff enough to hold together even highly jointed rocks during overcoring. The pressuremeter design allows a pressure test to be conducted in situ after the instrument has been installed to confirm the correct operation of all the strain gauges, obtain an indication of the elastic properties of the rock in situ, and, in some circumstances, determine the direction of the in situ stresses acting across the borehole. The elastic properties of the rock are also obtained in a biaxial test conducted after overcoring and from core collected from the pilot hole at the location of the instrument. Variations in the elastic modulus obtained during these various tests provide insight into the rock behaviour.

Recent developments in custom logging hardware have significantly improved the data density and the resolution of the strains able to be measured. For overcoring, strain changes are able to be recorded onto a laptop computer, processed, and displayed in real time during testing and overcoring. For monitoring, remote loggers are able to be deployed below ground at the borehole collar to take readings at intervals from a few minutes to a few days and remain unattended for six months or more.

1. Introduction

This paper describes the development history of the ANZI strain cell, the operation of the instrument, the test stages used in overcoring, and several examples of measurements that illustrate its use in a range of applications.

The ANZI strain cell has been developed with focus on simplicity of operation and providing high levels of redundancy to give a sense of the confidence that can be placed in each individual point measurement. Available analysis techniques for converting measured strains to stresses are limited by assumptions that the material is linear, elastic, isotropic and homogeneous. However, many rocks in which overcore tests are conducted are not ideal materials. These rocks are commonly not linear, elastic, isotropic, or homogeneous. Furthermore, the material properties of some softer rocks are commonly observed to change with stress.

Recognising that the calculation of stresses from strains is imperfect, the key to getting value from the measurement is gaining a sense of the confidence that can be placed in each measurement as a coherent indication of the stress at the point of measurement, and how well the rock properties can be approximated as an ideal material. In the authors' experience, not all measurements aimed at determining the in situ stress field or changes in stress are reliable, but having a basis to differentiate those that are is invaluable when developing an overall understanding of the stress environment and the rock behaviour within that environment. The design of the ANZI strain cell is focused on providing systems to allow the confidence in each point measurement to be assessed.

2. Development History

The ANZI strain cell has been developed over the last three decades through incremental improvements that have gradually increased its capability over time. The development history of the instrument is described in this section.

The original ANZSI strain cell (Mills & Pender 1986) was developed from 1980 to 1983 at the University of Auckland for the purpose of measuring three dimensional in situ stresses in coal. The instrument was primarily designed to reduce the tensile stresses generated in soft rocks at the borehole wall. The ANZSI strain cell was 38mm in diameter and carried nine strain gauges. The instrument was successfully used to measure in situ stresses in coal mines in New Zealand, Australia, and the United Kingdom as well as at several hard rock civil sites in New Zealand. For a several years in the late 1980's the instrument was produced under license by Mindata Pty Ltd. Figure 1 shows a photograph of the Mindata instrument and an original version of the instrument overcored in quartz-rich gneiss.

Figure 1: Photograph of original ANZSI strain cell design and overcore in gneiss.

In 1990, the instrument underwent a significant upgrade and a name change. The diameter was increased to 56mm diameter and manufactured on a hollow, tubular body. The number of strain gauges on each instrument was increased to 18, and the name was changed to ANZI (Australia New Zealand Inflatable) strain cell reflecting the instruments combined development history and essential mode of operation.

The larger diameter and tubular construction allows cables from up to two other ANZI strain cells located further into the hole to pass through the centre of the instrument. Up to three monitoring instruments can be installed in the one hole to reduce drilling effort. Two overcore instruments can be located back to back and overcored in the one operation to significantly reduce the time required to overcore 36 independent strain gauges.

From 1996 to 1998, a 29mm diameter version of the instrument was developed, also with 18 strain gauges. This instrument can be overcored using a BQ core barrel giving a 45mm diameter overcore. The smaller size was aimed at reducing the time taken to drill to depth. In coal mines, these instruments are able to be installed at 10-15m from an underground roadway within 2 hours of the start of drilling. However, the smaller drilling gear does not allow sufficiently good core recovery during drilling of the pilot hole to identify the optimal location where the instrument should be installed. The system has also been found to be too delicate for use with conventional drilling rigs. Nevertheless, this version of the ANZI strain cell is useful in specialist applications such as measuring bending stresses in diaphragm walls and tunnel linings or where size is a limitation.

Since 2001, ANZI strain cells have been deployed for monitoring the growth of full scale hydraulic fractures. The instruments have been found to provide useful information on fracture orientation, fracture growth, and stress changes induced by hydraulic fractures (Mills and Jeffrey 2004). Stress changes are able to be monitored on up to three instruments in a single BQ borehole placed at depths of 150m or more below the surface. Automated data logging of the strains increased the data density sufficiently to monitor hydraulic fracture growth in real time.

Since 2008, significant improvements in data logging capability have been made. With the aid of custom designed hardware and software, all 36 strain gauges of a two cell overcore instrument are able to be read, recorded, and displayed every few seconds on a laptop computer. This improvement not only allows overcoring to be conducted with a high data density at normal drilling rates but also allows other environmental factors such as drill rate and water pressure to be monitored and displayed.

A standalone, battery powered logging system has also been developed for remote logging applications. This system has the capability to read all 18 strain gauges as well as stable reference gauges embedded in the instrument at intervals ranging from a few minutes through to 90 hours. The logging system is typically deployed at the collar of the borehole and concealed below the surface to limit disturbance and vandalism. The logging system is capable of deployment with twice daily readings for periods of up to six months without need of a battery recharge.

Since 2009, ANZI strain cells have been overcored in HQ surface exploration boreholes, initially at depths of less than about 50m, and since 2011, at up to 150m below the surface. A program of deep hole overcoring in progress at the time of writing is aiming to increase the depth range to around 300m.

3. Operation of the ANZI Strain Cell

The ANZI strain cell is a strain measuring instrument that uses the overcoring method of stress relief to allow the in situ stresses to be estimated from the strains measured on variously oriented strain gauges bonded to the rock on the sides of a borehole. The instrument is also able to be deployed to monitor changes in stress that are induced by mining or other construction activities. The operation of the instrument is described in this section.

Figure 2 shows a photograph of the 56mm diameter version of the instrument. The instrument is essentially an inflatable membrane of soft rubber-like material with multiple strain gauges exposed on its outer surface. Eighteen electrical resistance strain gauges of various orientations are mounted flush on the outside surface of the membrane. When the membrane is pneumatically inflated during installation, the electrical resistance strain gauges become cemented directly to the borehole wall allowing direct measurement of strain changes in the rock.

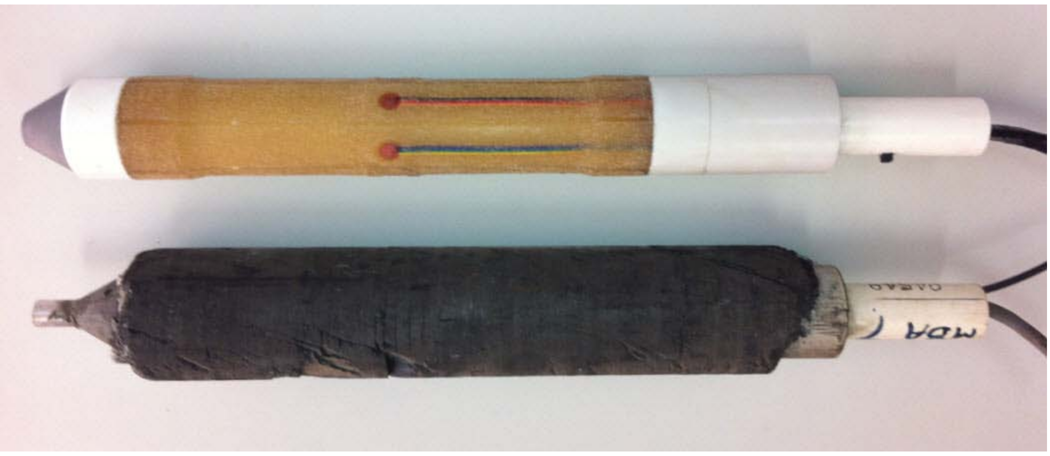


Figure 2: Photograph of single ANZI strain cell and successful overcore in coal.

The wiring of the strain gauges is embedded in the membrane so that the instrument is waterproof. Reference gauges, instrument orientation, water pressure, and temperature can also be monitored depending on the application.

The mechanics of overcoring are similar to other types of overcoring operations. However, an additional in situ pressure test is conducted prior to overcoring to confirm the correct operation of the strain gauges, and to measure the elastic properties of the rock in situ.

For overcore stress measurements, a configuration comprising two completely independent instruments that share the same cable is routinely used for overcoring. The two measurements are able to be conducted in much the same time as is required to do one measurement and the incremental cost of the second instrument is small in the context of the overall cost of the measurements. Each instrument is independently inflated and each is electrically isolated from the other.

For stress change monitoring purposes, up to three separate instruments are able to be spaced at any desired locations within the same borehole. Each of the three instruments has independent cables and inflation lines.

There are five stages in the standard ANZI strain cell test procedure: installation, in situ pressure test, overcoring stress relief, biaxial pressure test, and laboratory testing of the core recovered from the pilot hole. The overcoring and biaxial tests are essentially similar to procedures used for other types of stress relief instrument.

3.1 *Installation*

To install the ANZI strain cell, the access hole and pilot hole are drilled to the location of the test. The instrument is coated with custom designed epoxy cement and installed into the pilot hole to the required depth. The air pressure applied to the instrument causes most of the epoxy cement coating to be extruded away from the strain gauges and the membrane, leaving only a very thin 0.3-0.5mm thick layer. There is no requirement for the instrument to be installed near the end of the pilot hole as it can be inflated at any location. The pilot hole is typically drilled well beyond the measurement site and a suitable target horizon chosen on the basis of the core recovered. When the cement has cured, typically 6-12 hours depending on temperature, the strain gauges are bonded directly to the rock.

For stress measurements conducted underground in coal mines, tests are typically conducted in holes 10-15m long, drilled up at an angle from an underground roadway. In stress measurement tests conducted from the surface, instruments are commonly installed in pilot holes drilled from the end of HQ exploration holes.

3.2 *In Situ Pressure Test*

Once the cement has cured, a pressure test is conducted in situ using the ANZI strain cell as a pressuremeter or dilatometer. The pressures used in this test are kept relatively low to avoid disturbing the in situ stress field. The strain changes measured (typically 20-200 μS) are sufficient to confirm the correct operation of all the gauges, provide a measure of the in situ properties of the host rock before it is disturbed by drilling, and provide an indication of the in situ stress direction if rock properties allow.

The pressurised length of the ANZI strain cell membrane is designed to be four times the diameter of the borehole so as to generate near plane strain conditions during the in situ pressure test (Laier et al 1975). The increased length of the instrument also improves the length of overcore recovered in low strength or highly jointed rock.

For stress change monitoring, this pressure test provides an indication of the elastic modulus that is appropriate to use in the analysis to determine stress changes from the measured strain change. The pressure test can also be repeated at any time to confirm that the instrument is still fully operational.

3.3 *Overcoring*

The ANZI strain cell overcoring operation is conducted in much the same way as for other instruments that use the overcoring stress relief method. Direct bonding of the strain gauges onto the surface of the borehole means that the diameter of the overcore need only be slightly greater (10-20 mm) than the diameter of the instrument and the overcore does not need to remain completely intact for a valid result to be obtained. These characteristics extend the range of rock types and drilling environments in which the instrument can be used.

The configuration of strain gauges carried on the instrument can be varied to suit rock conditions. Typically, 5mm long gauges oriented in rosettes of three gauges each (0°, 45° and 90° to the axis of the borehole) are used. The 5mm long gauges minimise the strain averaging effect of longer gauges that can affect results in some stress fields. The gauges oriented at 0° and 90° orientations facilitate field interpretation of results.

The six rosettes of three gauges each are oriented at 60° intervals around the circumference of the cell to improve statistical confidence in the in situ stress measured (Gray & Toews 1974). Each rosette has one gauge oriented in a circumferential direction. Every second rosette has one gauge oriented in an axial direction. This combination gives 12 degrees of redundancy and two or more independent measurements of many of the individual strain components. For instance, there are three gauges that independently measure the one value of axial strain, three sets of directly opposite circumferential gauges, and three sets of directly opposite 45° gauges.

With the laptop logging system, strain readings are recorded every few seconds leading to a high data density. The general form of the overcoring strain changes can be used as a basis to identify rosettes of strain gauges that may not be behaving in a manner consistent with a strong result.

In situ stresses are determined from the measured strains using the technique described by Leeman & Hayes (1996) and variously enhanced by others. A minor correction can be made during analysis to include the effect of the 0.3-0.5 mm thick epoxy cement layer formed between the membrane and the rock using the analysis described by Duncan-Fama and Pender (1980), but the effects of this correction are slight. For all practical purposes, the strain gauges can be considered bonded directly to the borehole wall.

The membrane material has a modulus of elasticity of only a few MPa and so is soft enough to be ignored in the analyses. Significantly, the tensile stresses generated at the rock/instrument interface during overcoring are too low to overload either the epoxy cement bond strength or the tensile strength of the rock for most rock materials.

3.4 *Biaxial Pressure Test*

A biaxial pressure test is conducted after the core is recovered to measure elastic modulus and Poisson's ratio. The overcored rock annulus is incrementally pressurised in a biaxial cell that applies pressure uniformly around the annulus of the rock. The test provides measurement of the elastic modulus and Poisson's ratio at a range of different pressures and is useful as an indicator of the sensitivity of the rock to modulus variations with pressure.

There are some limitations with the biaxial pressure test for softer rocks because of the interaction of the biaxial cell membrane and the overcore. Development of a biaxial cell to reduce these effects is ongoing. If the core is damaged and a biaxial test cannot be completed, the elastic properties can be determined from the in situ pressure test and from laboratory tests of core recovered from the pilot hole.

3.5 *Laboratory Testing*

A laboratory test of the core recovered from the location of the measurement is tested in a multi-stage uniaxial compression test. Axial and circumferential strain gauges and the load/displacement records of the compression test are used to estimate the elastic properties of the rock in a range of load/unload cycles up to failure in uniaxial compression.

3.6 *Assessment of Elastic Properties*

The elastic properties of the rock mass are determined in three tests, the in situ pressure test conducted prior to overcoring, the biaxial pressure test conducted after overcoring, and laboratory tests on core recovered from the pilot hole. These three essentially independent measurements are conducted on the rock in various stages of disturbance and at various levels of stress.

These different conditions provide insight into the rock behaviour and the impact of drilling on the rock as it is unloaded and recovered from the hole. In an ideal, homogeneous, linear, elastic, isotropic material, all three tests would indicate the same values of elastic properties. However, variations are commonly observed, particularly in softer rocks, and these variations have provided useful insights into the material behaviour of these rocks.

4. Example of Overcore Measurements

Figure 3 shows an example of a stress measurement test conducted in a sandstone material using the ANZI strain cell in a vertical hole. The pressure test indicates the gauges are operating correctly prior to overcoring and the elastic modulus of the sandstone material in situ is able to be calculated if Poisson's ratio is known from other tests or can be assumed.

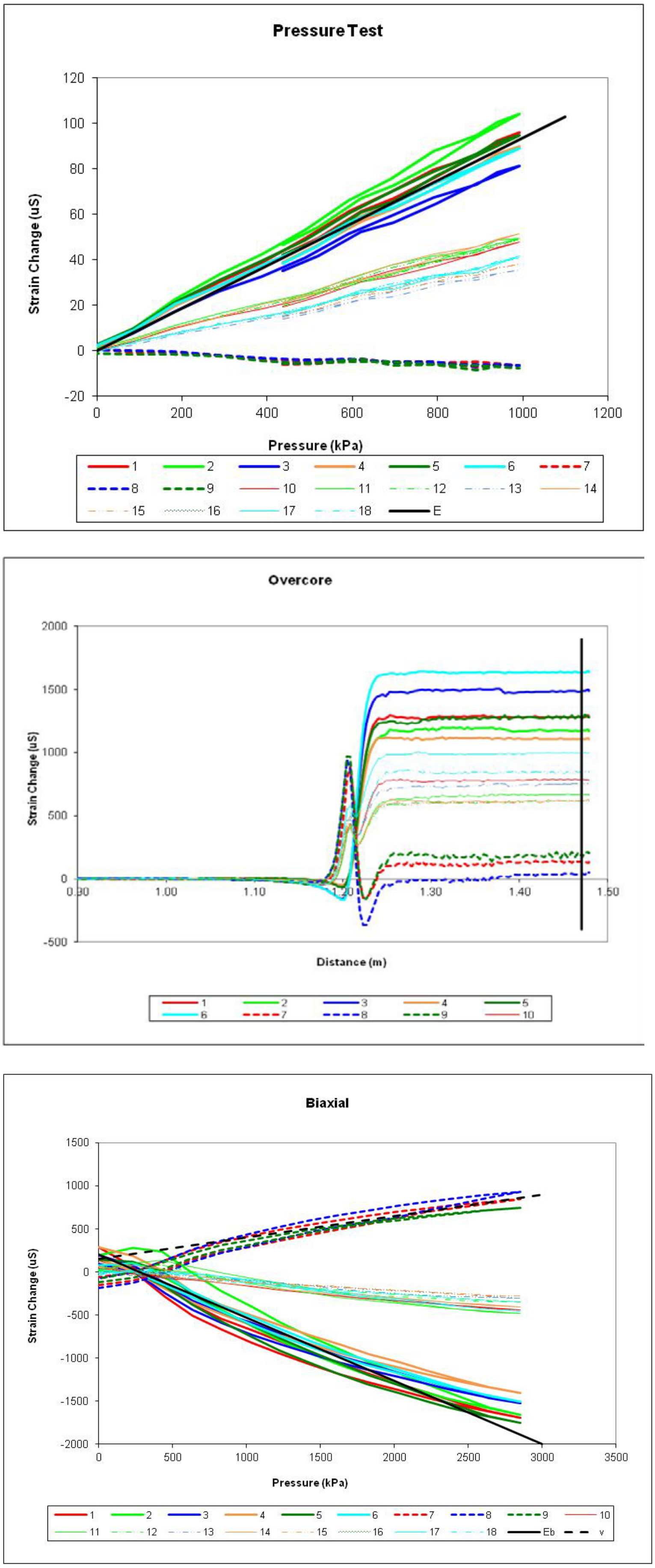


Figure 3: Example of strain measurements from ANZI test in sandstone strata.

Variations in the elastic modulus related to in situ stress concentrations around the borehole are evident in the pressure test. These variations can be used to infer the direction of the horizontal stresses perpendicular to the axis of the hole. The form of the overcoring test indicates that the instrument has registered the stress relief in a manner that is smooth and consistent with the behaviour expected in a meaningful measurement. Independent strain gauges on opposite sides of the instrument register close to identical strain changes giving confidence in the result. The three axial gauges also indicate similar strain magnitudes. The biaxial test shows a non-linear response that reflects the sensitivity of the elastic modulus to the first stress invariant (the sum of the three principal stresses). Variability in modulus can also be associated with eccentricity of the pilot hole.

5. Monitoring Stress Changes Associated with Hydraulic Fractures

This section presents an example of stress change monitoring around full scale hydraulic fractures to illustrate this application of three dimensional stress change monitoring. Hydraulic fracturing has long been used to induce fractures in rock strata. However, it is unusual to have the opportunity to measure the actual stress changes induced in the rock mass by full scale hydraulic fractures. Mills et al (2004) describe one of several field measurement programs where ANZI strain cells have been used to measure the changes in stress in a rock mass as a hydraulic fracture approaches and passes an instrument. Four ANZI strain cells were installed in two BQ holes drilled downward some 45m at 60° from horizontal (Figure 4). These two monitoring holes were located either side of the main fracture injection hole. The hydraulic fractures were initiated at a level below the level of the monitoring holes so that the monitoring holes had no influence on fracture growth.

Figure 4: Monitoring ANZI strain cell about to be installed 40m into a BQ borehole.

All strain gauges were logged at about 15 second intervals through the hydraulic fracture treatments. A reference gauge installed on the instrument but isolated from any change was also logged. Any signal noise measured on the reference gauge was assumed to have affected all gauges and was subtracted from the readings on other gauges. Using this approach and a moving average, signal noise was reduced to about ±3μS.

Figure 5a shows an example of the strain changes measured during the hydraulic fracture treatment on one of the ANZI strain cells. The injection flow rate for the hydraulic fracture is superimposed onto this plot. Figure 5b shows stress change determined on a plane approximately perpendicular to the plane of the hydraulic fracture and the injection pressure in the injection borehole. Both plots have the same time base.

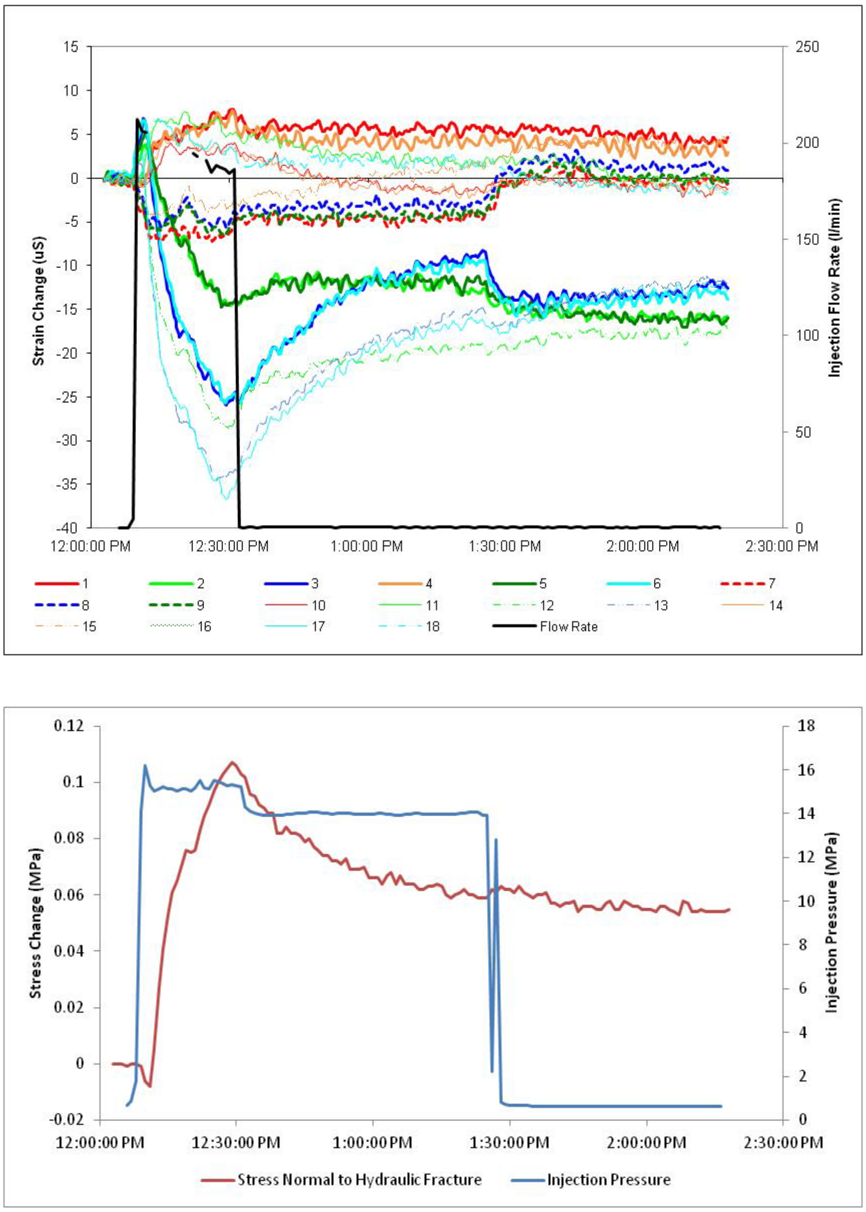


Figure 5: **a) Strain changes measured during a hydraulic fracture treatment and injected flow rate.**
b) Stress change normal to hydraulic fracture and fluid injection pressure in the hydraulic fracture.

There is a strong correlation with the various stages of injection. From an initial steady state, strain changes are observed soon after the commencement of the treatment. These strains peak when the injection stops (shut-in) and drop back to a final steady state once the injection pressure in the fracture is released (flow-back).

There is also a good correlation between independent gauges measuring the same strain component but on opposite sides of the borehole (1 and 4, 2 and 5, 3 and 6, 10 and 14, 11 and 16, and 13 and 17) and the three independent measurements of axial strain (7, 8 and 9). These close correlations give a high level of confidence in the result despite the relatively small strain changes observed.

The stress changes calculated from the measured strain changes indicate an initial tensile change as the hydraulic fracture approaches the instrument and the rock is stretched ahead of the fracture, followed by a compressive change as the tip of the hydraulic fracture passes near the instrument and the rock is compressed by the fluid pressure within the fracture.

In this application, the ANZI strain cells were able to monitor low level stress changes (<0.1MPa) within the rock mass with a high level of confidence. These measurements helped define the orientation of the hydraulic fracture, the growth rate, and the peak and residual stress changes locked into the formation as a result.

6. Monitoring Mining Induced Stress Changes

This section presents an example of longer term monitoring at a sandstone outcrop containing a large number of Aboriginal grinding grooves.

Longwall mining activity in the Southern and Western Coalfields of NSW is often conducted in areas where there are sandstone outcrops that require protection from the impacts of mining subsidence. These features include cliff lines, overhanging waterfalls, river channels, as well as archaeological heritage sites such as rock shelters and grinding groove sites. Conventional surveying is typically not sensitive enough to detect the low level ground movements that precede perceptible impacts. However, stress change monitoring is several orders of magnitude more sensitive than conventional surveying and has been successfully used to provide early indication of the nature and magnitude of ground movement.

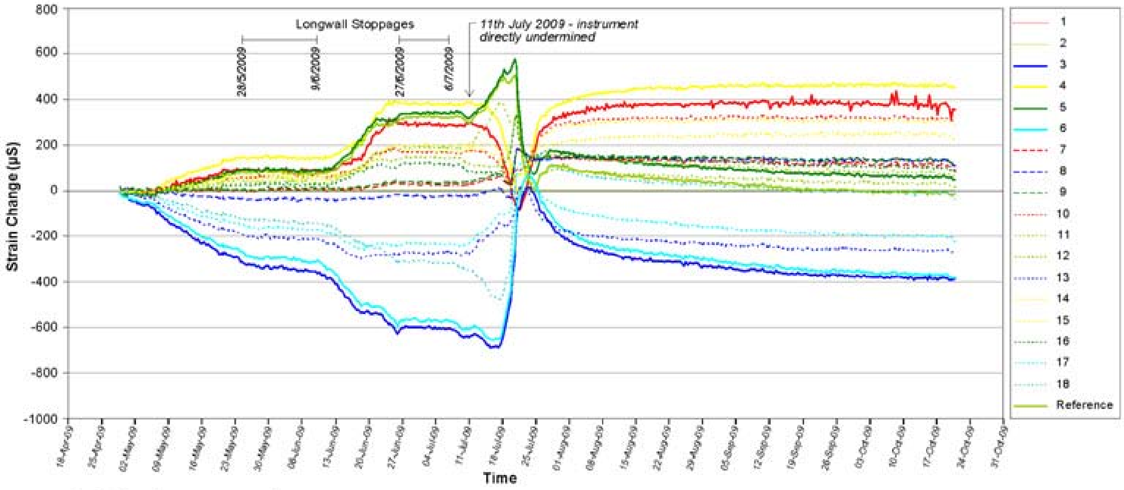
The site discussed in this section is approximately 700m from the start of a longwall panel at CH1145m and approximately 80m from the edge of the longwall panel. The overburden depth is approximately 245m. A double ANZI strain cell was overcored to determine the initial state of stress in the rock strata. A single monitoring cell was then installed in a vertical hole 12.9m below the surface. This instrument was installed, and monitoring began, when the longwall had retreated approximately 37m from its starting position at CH1837m.

Figure 6 shows the records of strain change measured on the instrument during retreat of the longwall panel. The strain changes are plotted against time and against face position. For the first 100m of longwall retreat, the progression of goaf fracturing upward through the overburden strata is apparent. Once the goaf fracturing reaches the surface, and subsidence begins to occur, the rate of change of strain observed at the grinding groove site increases.

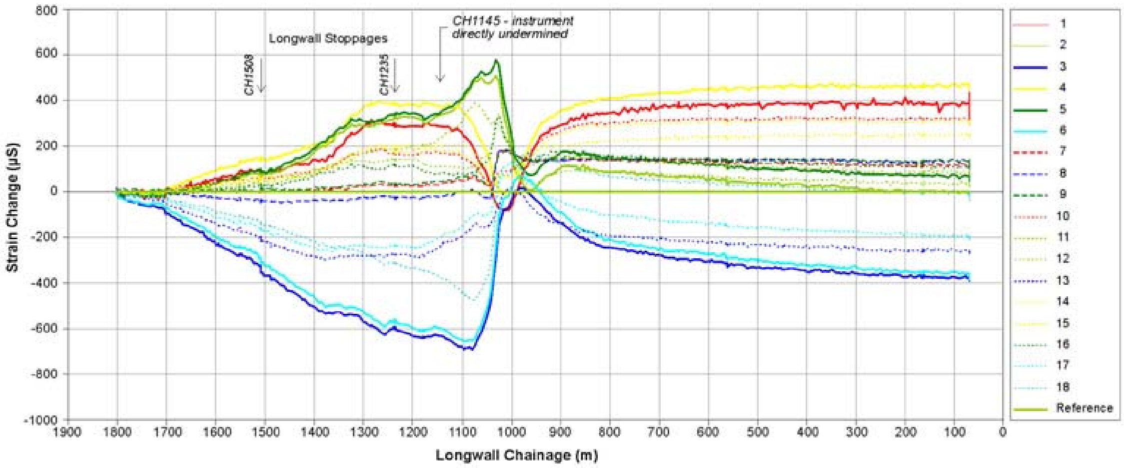
The longwall face was delayed for several weeks on two occasions due to adverse mining conditions underground. These delays are clearly evident in the strain readings plotted against time even though the instrument is located some 400m and 110m respectively from the longwall face for the two events and 230m vertically above the mining horizon.

An outcome of these measurements is the observation that the stress changes at the site are entirely a function of the geometry of the approaching longwall for the first stoppage as evidenced by the absence of change when plotted against face position. The response is essentially elastic. When the longwall approached within approximately 150m of the site, the strain changes no longer continued to build at the same rate as previously. The strain changes reached a plateau at this point and did not increase further until the first signs of perceptible fracturing were observed soon after the site was directly undermined.

The large changes in strain observed during the period when the longwall face is 60m past through to about 240m past the site are consistent with the ground movements that are routinely measured by conventional subsidence monitoring techniques.



a) Strain changes versus time.



b) Strain changes versus longwall chainage.

Figure 6: ANZI strain cell monitoring of sandstone features above a longwall panel.

7. Conclusions

The ANZI strain cell has various operational features and analytical simplicities that have enabled in situ stresses to be successfully determined and stress changes to be successfully monitored in a wide range of rock types and applications over the last several decades.

The high levels of redundancy in both the instrument and the measurement technique are designed to provide an indication of the confidence that can be placed in each result and to enhance the understanding of material behaviour.

Examples of overcore measurements and stress change monitoring are presented to show the way that the instrument has been deployed and how the results allow the development of understanding of rock behaviour on both a large scale across entire longwall panels and at a micro-scale as stress concentrations around single boreholes.

The capability to deploy three dimensional stress change monitoring ANZI strain cells to distances of 50-150m from the surface or from underground openings enables the instruments to be located into areas of interest. These instruments have enabled high confidence monitoring of hydraulic fracture growth even for very low levels of strain change thereby allowing determination of fracture orientation, growth rate, and residual stress change generated by the hydraulic fracture.

The capability to record strain changes in remote locations over extended periods of time enables the monitoring of longer term, large scale strain changes for subsidence impact assessment and general understanding of the ground behaviour. Strain changes associated with longwall mining have been monitored for significant distances (700m in the example presented because that was the distance of the instrument from the start of the panel) well before they become detectable by conventional subsidence monitoring techniques.

8. References

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